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Heat Storage in Future Zero-Energy Buildings

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ABSTRACT: Institute of Materials & Machine Mechanics of Slovak Academy of Sciences (IMSAS) possesses the unique experience in the field of production of heating/cooling wall and ceiling panels based on aluminium foams for future energy autonomous houses and buildings. These novel heating/cooling panels have been developed and successfully tested in pilot application in 260 m^2 open space office room. The low heat capacity of aluminium foam allows changing the temperature very quickly, whereas the temperature of the entire foam volume is always very uniform due to excellent thermal conductivity of aluminium cell walls. The heat is dissipated by foam using foamed-in tubes, which are completely embedded in the foam, keeping excellent contact to cell wall aluminium. Good thermal conductivity of the foam resulted in short length of embedded tubes, what is beneficial for low flow resistance and necessary pumping systems. The foamed panels can be partially impregnated at facing side by appropriate plaster, which improves the appearance and also serves as an absorber of potentially condensed air humidity. The developed panels provide an excellent alternative for large built-in ceiling radiators for efficient heating or cooling of rooms using low potential energy resources. The most appropriate ways of using these panels, which are able to increase extremely energy-efficiency in buildings have been outlined in this contribution. Moreover, technological solutions based on ability to store solar thermal energy effectively within the energy efficient buildings are introduced to scientific community in this contribution. The local thermal energy storage must provide the required flexibility to match the heat demand and supply because thermal energy cannot be transported over long distances without significant losses. Solar heat supply fluctuates not only between day and night, but extremely high fluctuations are problematically solvable mainly between summer and winter. In order to use the energy from sun to its maximum, the storage should be capable not only for short periods (hours and days) but also for long-term, e.g. seasonal heat storage. The advanced technologies for short-term storage as well as seasonal storage of solar heat obtained by thermo-solar collectors which allow to reduce energy consumption significantly during winter by interior heating and hot water generation in energy-efficient buildings are discussed in this study.

KEYWORDS: heat storage, energy-efficient buildings, thermo-solar collectors, ceiling heating/cooling

I. INTRODUCTION

Zero-Energy Buildings (ZEBs) are buildings, which has a total annual sum of zero exergy transfer across the building-district boundary in a district energy system, during all electric and any other transfer that is taking place in a certain period of time [1]. The energy needs for ZEBs are greatly reduced through efficiency gains such that the balance of the energy needs can be supplied by renewable technologies. ZEBs optimally combine commercially available renewable energy technology with the state of the art energy efficiency construction techniques. There are no fossil fuels consumed in ZEBs and its annual energy consumption therefore do not exceed annual energy production.

The energy systems providing supply to future buildings will be surely based on entirely CO_2-free energy production. The development of energy supply and storage technologies should lead to economy based entirely on emission-free and inexhaustible energy sources, such as a solar, wind or geothermal. The electricity and energy efficiency to produce it will play still quite a long time an important role in fulfilling constantly growing global energy demand. The challenges of sustainability, such as climate change, diminishing natural resources and further negative environmental effects necessitate a transition from power production based on the use of limited energy sources obtained from fossil fuel combustion to the more efficient energy systems with significantly lower emissions. The future economy will utilise solar energy either directly as solar power or heat or indirectly as hydro, wave and wind energy, bio-energy and geothermal heat. The future eco-cities will be based on smart grids with eco-efficient construction utilizing exclusively ecological engineering materials, sustainable methods of energy production, transportation and storage as well as various advanced energy efficient heating/cooling solutions.

II. ADVANCED MATERIALS AND METHODS OF HEAT STORAGE IN ZERO-ENERGY BUILDINGS

The most convenient way how to decrease energy demands in the buildings is the utilization of renewable energy sources – the solar, wind or geothermal one. A main drawback of the solar source is its irregularity whereas it produces a lot of excess heat during the peak time and during the night this excess heat is almost not possible to use. In case of cooling, it is an issue to eliminate overheating from the solar source during the day what also requires additional energy inputs. That is why it is important to focus on development of new systems which will be able to cover these natural energy fall-outs by storing and subsequent later evolving the accumulated heat or cold according to the day-night cycle.

The thermal energy can be stored in standard buildings into massive inserts (i.e. clay bricks), but only sensible heat can be stored and the massive materials evolve this heat only in hand with continuous change of their temperature in this case. The sensible heat can be stored also if the Phase Change Materials (PCMs) are used for thermal energy storage. However, their most important property is the phase change solid-liquid and vice versa at the temperature range between 23°C and 28°C. During this change, a lot of latent heat is evolved or absorbed at almost constant temperature. The utilization of PCMs in larger volumes is strongly limited because of its low thermal conductivity. In this case solidification starts on the surface creating thus an isolating solid crust. That is why there is a need to combine PCMs and porous materials with higher thermal conductivity. Small empty pores can be filled with PCMs what ensures phase change in whole volume without creation of the isolating solid crust.

The aluminium foam panels made by foaming of foamable precursor with stainless tubes embedded in the structure of foam are therefore the most promising solution for energy efficient heating and cooling of walls/ceilings in interiors of buildings. The huge application potential mainly in the building and shipbuilding industry is expected thanks to their quick response to temperature changes due to excellent heat conduction of porous aluminium structure, lightweight design, self-supporting capability as well as shape and surface flexibility. The large active surface of foamed panels with extremely quick response to temperature changes enables to use heating/cooling fluids with the temperature nearly the same as is the achieved and maintained room temperature of interior air. This allows utilize various available alternative energy resources such as solar or geothermal energy very effectively for heating during winter, or even simply cold air during summer nights for cooling. The ceiling panels made of aluminium foam (Fig. 1) supplemented with system containing the heat storage reservoir enables significantly to increase energy efficiency of interior heating and cooling. Moreover, this system enables to spend or release into the interior certain amount of heat at constant temperature in the case that aluminium foam is filled with PCMs melting or solidifying at desired temperature. This feature makes possible in combination with smart temperature control systems further energy cost savings for heating/air conditioning systems of future ZEBs.

III. STORAGE OF HEAT FOR HEATING AND HOT WATER GENERATION

The heat and coldness demand of ZEB built in the temperate zone during summer can be completely fulfilled using solar heat (alternatively supplemented by photovoltaics) in the case that (i) the thermo-solar collectors are used as the heat source for hot water generation, (ii) the heat from interiors is transferred via water flowing through lightweight large area wall and ceiling panels made of aluminium foam to the well built in the close vicinity of the building in order to dissipate the heat to the relatively cold ground and in addition, it can be assumed also that (iii) novel advanced technologies for short-term storage of the heat obtained during day using PCM-based materials are applied in order to have stored heat available during night. However, during winter the heat demand is largely exceeding the solar supply. The further technical solution which enables significantly to increase energy efficiency of heating and cooling in ZEBs is to store the excess of solar energy in the summer, and to use it to fulfil the heat demand in the winter. It is indisputable that storing of heat efficiently for long time periods is necessary, but hot water and PCM storages require large volumes, become expensive and have significant heat loses when used for long time.

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An alternative storage technology is based on the use of thermo-chemical materials (TCMs), which can store thermal energy in the reversible breaking and restoring of the chemical bond between two molecules. This chemical bond has a higher energy density than heat stored as sensible heat (e.g. hot water storage) or heat stored in a phase change (e.g. ice or PCM storage). The energy can be stored in a TCM for a very long time without any loss of the stored energy of the chemical bonds. TCMs such as e.g. salt hydrates store heat by means of chemical processes using the reversible reaction: A + B ⇔ C + heat (Fig. 2). The basic principle of this method lies in the fact that a suitable chemical compound is heated to the point where it dissociates into two (or more) other compounds, which can be stored separately. When these compounds are later recombined, the original compound is formed again and the stored heat is released. Magnesium chloride hexahydrate ($MgCl_2.6H_2O$) is one of the most promising and relatively cheep TCM for seasonal heat storage [4].

(a) (b)

(c) (d)

Fig. 1. Ceiling heating/cooling panels made of aluminium foam developed by IMSAS (a), example of their surface design using thin-walled composite surface foil with trade mark MWM Design – Clasic Stone produced by German company MWM GmbH & Co KG, Arnsberg (b) [2, 3], installation of aluminium foam panels in SmartGrid laboratory of IMSAS in Bratislava (c) and in the open office space area 260 m^2 of company Sapa Profily a.s. in Ziar nad Hronom, Slovakia (d).

The promising result for the future use of TCMs for seasonal domestic heat storage for space heating and hot water generation was introduced in [4]. According to small scale study [5] the dehydration of 245 g $MgCl_2.6H_2O$ and its subsequent hydration at 12 mbar vapour pressure (corresponding to evaporation at a typical borehole temperature of 10°C) gives a temperature rise of 20°C. The upscaling of the reactor is possible and a reasonable performance can be obtained even with a low cost simple reactor. The development of proper reactor design at reasonable production costs will be therefore in the near future the subject of further studies aimed to significant reduction of costs necessary for the year-round operation of ZEBs.

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Nevertheless, excessively high current price of both the batteries for storage of renewable energy in the form of electrical energy and the building-integrated hydrogen storage systems is today the main obstacle for application of these technologies in small ZEB. The potential to reduce the energy consumption of e.g. small family house by storing energy obtained by renewable sources directly in the house or in its immediate vicinity is therefore extremely hard achievable target, if batteries, flywheels or hydrogen systems are used for this purpose. The energy storage systems based on thermal storage and also systems based on compressed air energy storage as well as pumped hydro power storage seem to be unavoidable in order to have return-on-investment period below ten years in the case of small ZEB.

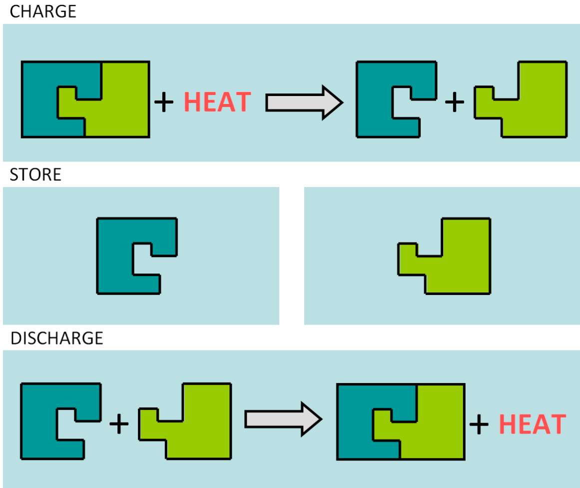

Fig. 2. Concept of thermochemical heat storage.

IV. TESTING OF HEAT EXCHANGER FILLED BY PCM BASED MATERIALS

In order to test the various methods for production, transfer and consumption of energy obtained from renewable sources a Smart Grid laboratory (Fig. 3) equipped with 29 kW photovoltaic power plant, concentrated thermo-solar collectors, heat pumps for conversion of geothermal energy from four drilled 100 m deep drill holes, heat storage vessels and advanced control units has been built recently in the experimental hall of IMSAS in Bratislava. For IMSAS this creates an extraordinary possibility to build up the unique competency in this rapidly developing and very important research field. The orientation of future institute’s research activities towards the research on advanced materials for the efficient use of renewable energy is thus foreseen.

A simple test of heat transfer behaviour using heat exchanger filled with PCM immersed in a barrel with water has been done in above mentioned Smart Grid laboratory in order to verify the ability of PCM to store latent heat of its liquid – solid conversion. The heat exchanger consisting of 6 pieces of tubular Al profile (520 × 50 × 50 mm) has been filled by PCM (trade mark RUBITHERM® RT28HC produced by German company Rubitherm Technologies GmbH, Berlin) with phase transition temperature of 28°C [6] as shown in Fig. 4. The water heated by the thermostat flowed through the central opening of Al profiles and side openings have been filled by PCM. The total weight of Al profiles connected in series was 6.8 kg, weight of PCM was 1.7 kg and the volume of the water in testing barrel was 56 litres. The water has been heated by constant power of 1600 W until the temperature reached 62°C. It has been compared the speed of free water cooling to a temperature of 24°C in the case of heat exchanger with and without PCM filling.

As can be seen from Fig. 5, during free cooling at ambient room temperature is the time required to attain the temperature of heat exchanger surface 24°C more than 6 hours and 40 minutes longer in the case that the heat exchanger is filled by 1.7 kg of PCM in comparison with its behaviour without PCM filling. Fig. 6 shows comparison

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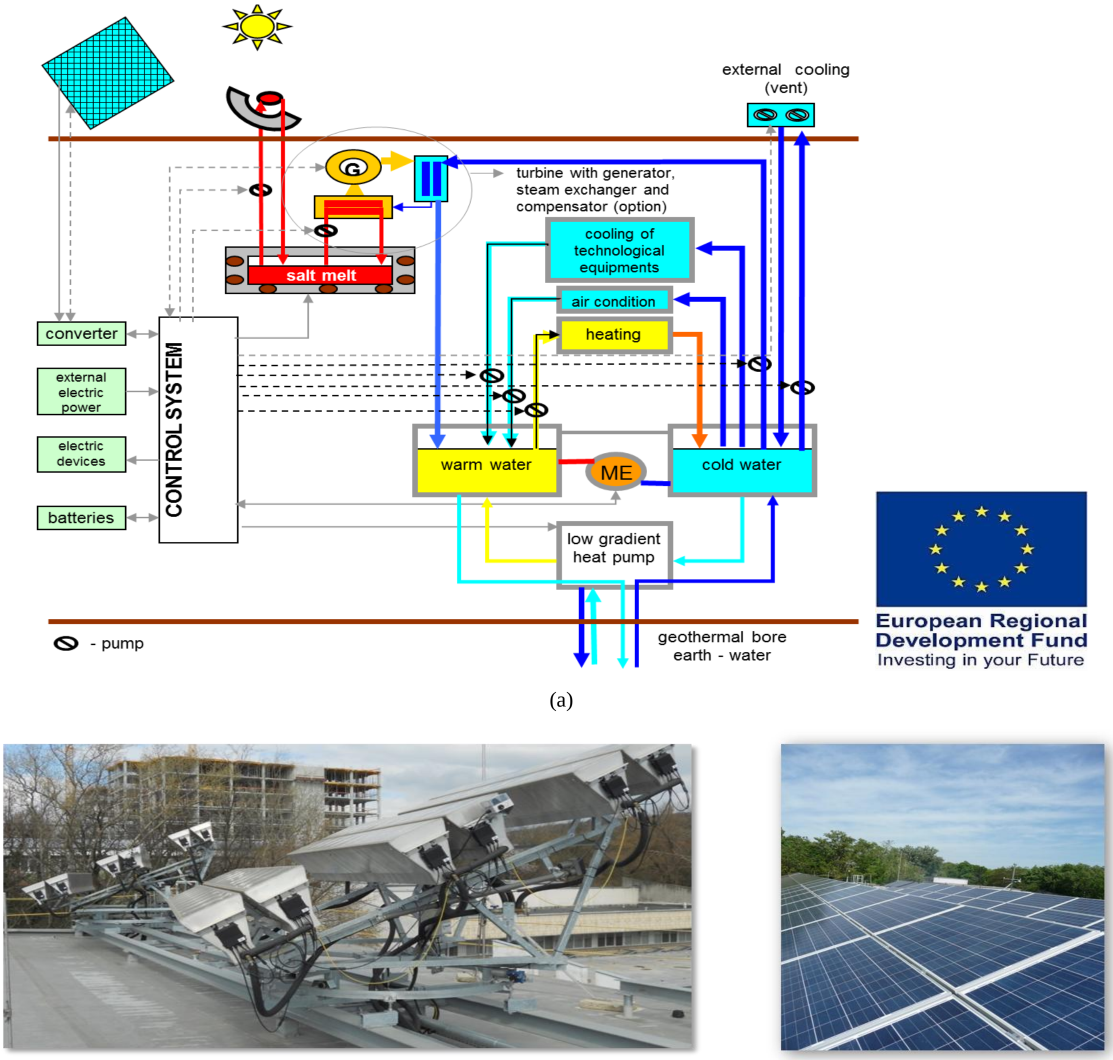
of the energy necessary for heating of aluminium profile, PCM and water in the barrel during heating the heat exchanger from room temperature to the temperature of 62°C.

Nevertheless, the considerable disadvantage of PCMs used for heat storage is the physical phenomenon of their extremely low thermal conductivity. In the case of PCM with trade mark RUBITHERM® RT28HC is the thermal conductivity only 0.2 W/m·K (for a comparison the thermal conductivity of various aluminium alloys is in the range from 76 to 235 W/m·K).



(a)

(b)

(c)

Fig. 3. Smart Grid laboratory equipped with 29 kW photovoltaic power plant established recently in the experimental hall of IMSAS in Bratislava: circuit diagram of Smart Grid Laboratory equipment (a), concentrated thermo-solar collectors (b) and 29 kW photovoltaic power plant (c).

The liquefied surface of PCM is during accumulation of latent heat acting as a thermal insulation which considerably prevents against quick phase conversion of whole PCM volume to liquid state. When the accumulated heat is re-releasing, the situation is the same, i.e. solidified surface of PCM is acting as a thermal insulation preventing phase conversion of PCM to solid state in this case. However, this disadvantage can be from technological point of view very

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simply eliminated in such a way that the PCM is admixed with the certain conductive material in the form of e.g. metallic powder particles, fibres, granules, etc. with considerably high thermal conductivity. The heat is in this case very efficiently transferred through the interface between this filler and PCM within the whole its volume. An innovative structural design of heat exchanger filled by this way with such PCM-based composite material is shown in Fig. 7. The granules of aluminium scrap are admixed to PCM in order to facilitate improved heat transfer from the whole volume of PCM to the surroundings during storing as well as also during dissipating of heat due to thermal conductivity enhancement of material for heat storage.

Fig. 4. Test layout during experimental investigation of thermal storage ability of PCM using heat exchanger made of aluminium profiles.

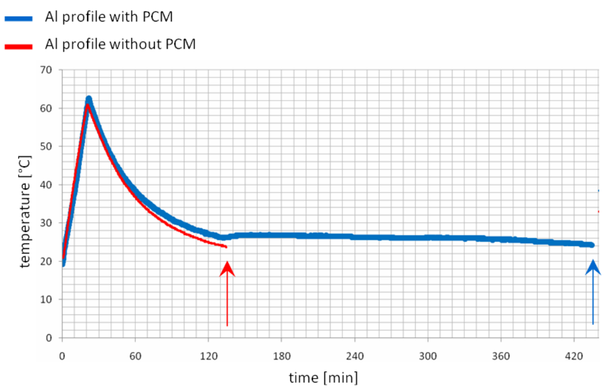

Fig. 5. Comparison of cooling rates of heat exchanger filled by PCM (blue curve) and heat exchanger without PCM filling (red curve) during thermal storage ability testing of PCM (the temperature is measured at the surface of aluminium profile in the mid-point of trajectory of heating/cooling water flowing through the heat exchanger).

Al profile:	E_1 [MJ]	E_2 [MJ]	E_3 [MJ]	E [MJ]
without PCM	0.25			**0.25**
with PCM	0.27	0.56		**0.83**
without PCM in water	0.27		8.56	**8.83**
with PCM in water	0.26	0.56	7.36	**8.18**

Fig. 6. The comparison of the energy necessary for heating of aluminium profile, PCM and water in the barrel during heating of the heat exchanger from room temperature to the temperature of 62°C (E_1 – energy for heating of 6.8 kg aluminium profiles, E_2 – energy for heating of 1.7 kg PCM, E_3 – energy for heating of 56 litres of water, E – total energy for heating of whole heat exchanger immersed in the water).

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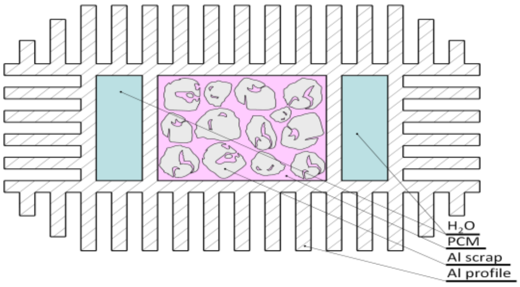
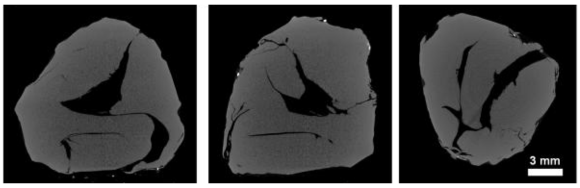


(a)

(b)



(c)

Fig. 7. An example of novel heat exchanger design for heat storage filled by PCM based materials (a), granules of aluminium scrap (b) and cross-section of an aluminium scrap granule in three mutually perpendicular planes obtained by high-resolution x-ray micro tomography method (c).

V. CONCLUSIONS

The aluminium foam panels provide an excellent alternative for large built-in ceiling radiators for efficient heating or cooling of rooms using low potential energy resources. Porous structure of aluminium foam allows absorb or dissipate very homogenously latent heat at almost constant temperature if PCMs with phase change at the temperature range between 23 °C and 28 °C are used for storage of the heat obtained from renewable energy sources. These features of aluminium foam panels in combination with smart temperature control systems allows significantly reduce energy consumption of heating/air conditioning systems of future ZEBs. The energy storage systems based on thermal storage (maybe also in combination with both the compressed air energy storage and the pumped hydro power storage) seem to be unavoidable in order to have return-on-investment period below ten years in the case of energy efficient small family houses.

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